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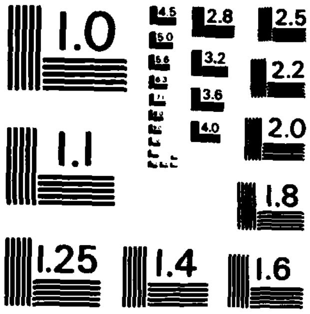

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A new empirical model of the geomagnetic variation in the earth's thermosphere and exosphere is presented. The form of the new model is similar to that developed earlier by Jacchia et al. from ESRO 4 mass spectrometer data. It differs from the earlier formulation in that it incorporates the variation with local magnetic time, allows the shape → cont

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cont of the latitudinal response to vary with the level of geomagnetic disturbance and includes a latitude-dependent term in the thermal component of the variation. A new index of disturbance is also introduced that is designed to take into account the effect of the prior heat input associated with geomagnetic activity. The model parameters are essentially those deduced from analysis of the ESRO 4 mass spectrometer data. Some refinement of the parameters is to be expected, especially in regard to separation of thermal and mass transport effects in low latitudes.

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FIGURES

A NEW MODEL OF THE GEOMAGNETIC VARIATION IN THE UPPER ATMOSPHERE

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1.0 INTRODUCTION

Large variations in the density of the thermosphere and exosphere in association with geomagnetic disturbances were first detected by Jacchia (1959, 1961) in the drag on artificial satellites. Densities obtained from the analysis of drag were then used extensively to study and model this geomagnetic variation in the upper atmosphere. Model development based on drag analysis culminated with the model derived by Jacchia *et al* (1967) that was subsequently incorporated, with only slight modification, in the 1972 CIRA reference atmosphere and other general models of the upper atmosphere derived from drag analysis.

The models of the geomagnetic variation based on drag analysis were extremely simple in form and usually represented the variation as being uniform over the globe. As it turns out, the geomagnetic variation is extremely complex in form but, while this was certainly suspected, the drag data revealed few details because of their poor resolution. It was not until data from *in situ* accelerometer and mass spectrometer experiments became available that the geomagnetic variation could be modeled in any detail. The process is still far from being complete, however.

There are, at present, two models based on high-resolution data in use. One of these is that of Jacchia *et al* (1976, 1977) that is incorporated in Jacchia's most recent general model of the thermosphere and exosphere (1977). The other is that of Hedin *et al* that is incorporated in the MSIS model (1977a, 1977b, 1979). Here, we will describe initial efforts directed toward extending and improving the model of Jacchia *et al*. In this, we have four main aims. These are:

1) To incorporate the variation with local magnetic time. As it is now, the model includes only the mean variation with latitude. The local time variation is extremely complex, but the main features are quite significant and can be included without too much difficulty.

2) To allow the form of the variation to vary with the level of disturbance. Slowey (1981) has shown the latitudinal form of the variation to broaden in high latitudes with increasing levels of disturbance. This effect appears to be related to a shift in the location of some of the heat input. Meng (1982) has reported that the polar cusp region shifts significantly toward lower latitudes for larger disturbances.

3) To allow for the prior heat input in establishing an index for the level of disturbance. The K_p geomagnetic index admittedly leaves much to be desired as an indicator of disturbance in the atmosphere. It is increasingly clear, however, that there is much to be gained by taking account of the persistence of the effects of disturbance. Theoretical calculations such as those by Fuller-Rowell and Rees (1981) and the semiempirical models of Hedin et al (1981) indicate that the disturbance history over the preceding 5 days is probably significant.

4) To correct what is now seen as a rather serious flaw in the original model in not permitting an increase in exospheric temperature at the equator. The effect at the equator was modeled entirely in terms of an "equatorial wave" of density that was assumed to originate in high latitudes and progress towards the equator. While it is clear from the mass spectrometer data that such a wave is a significant component of the low latitude response, it is now equally clear that a thermal component also exists in low latitudes. Separating the two components in data from a single height or from a limited range of height, which was all that was available to us until recently, is extremely difficult, however, and a final determination of the relative importance and extent of the equatorial wave will depend on future analysis of data from lower heights.

2.0 NATURE OF THE VARIATION

In figure 1 we show a plot of molecular nitrogen density measured during a portion of one orbit of the Atmosphere Explorer-C satellite by the OSS mass-spectrometer. The data were collected during a period of relatively high geomagnetic activity (1.5 hours earlier, K_p was 6+) and when the satellite was in a nearly circular orbit. Since the height varied so little, in was safe to reduce them to a single height for purposes of analysis and that is the way they are shown here. The abscissa is the time in minutes, starting from an arbitrary zero point. The scale of the ordinate of the N_2 number density is not shown, but it represents the change in the logarithm of the number density. The maximum density here corresponds to a change of 0.5 in $\log_{10} n(N_2)$, an increase by a factor of more than 3 in number density, relative to the density at the origin of the plot. The smooth curve at the top of the figure is the (adiabatic invariant) geomagnetic latitude plotted on the scale at the left of the figure.

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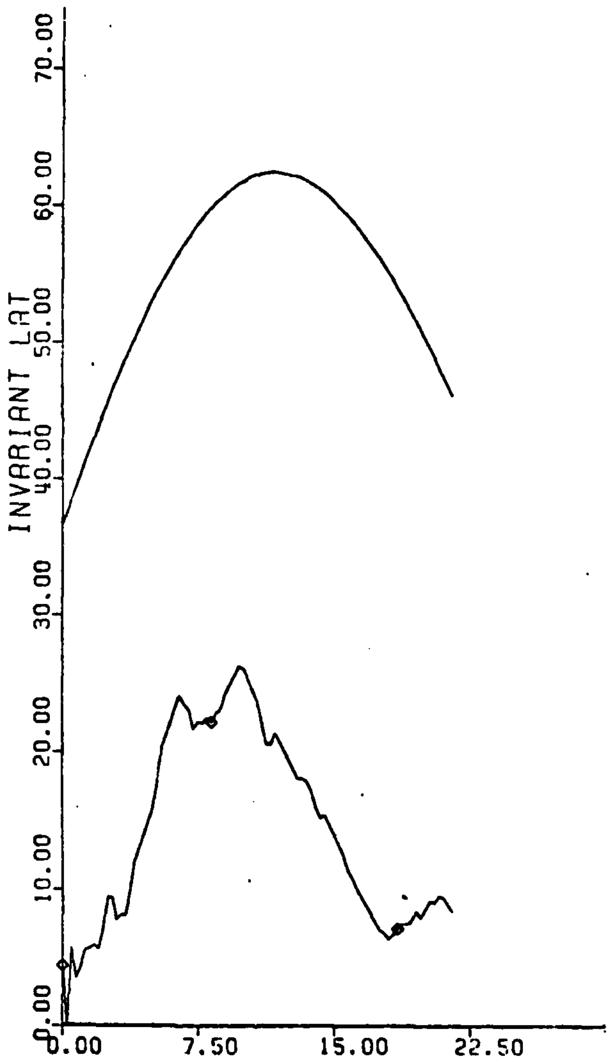

Figure 1. Logarithm of N_2 density at a height of 250 km as measured by the OSS mass spectrometer on AE-C during a portion of orbit 4919. The abscissa is the time in minutes from an arbitrary zero point and the ordinate is not given (see text). The smooth curve is the invariant geomagnetic latitude with ordinate scale on the left.

The strong dependence of the geomagnetic variation on geomagnetic latitude is well established and we can see it in orbit after orbit of the AE-C and other satellite-borne mass spectrometer data, not only in N_2 but in all constituents. Not all constituents behave the way N_2 does, however, and this is another important aspect of the geomagnetic variation. The behavior of the lighter constituents, such as He, is just the opposite of that of N_2: their number densities decrease where those of N_2 increase. And the density of atomic oxygen, which is of primary importance as far as total density is concerned throughout most of the thermosphere, may either

increase, decrease or remain unchanged. In addition to a purely thermal effect, there is another factor involved in which the molecular mass is very important. We shall represent this factor in terms of a variation in the height of the homopause.

The variation is also clearly not just dependent on the geomagnetic latitude. There are two distinct maxima in the data of figure 1 that represent separate regions of enhancement in the vicinity of the auroral oval. As the figure demonstrates, there is also an appreciable over-all asymmetry with respect to geomagnetic latitude.

3.0 FORM OF THE MODEL

The model of Jacchia <u>et al</u> represents the density and composition changes that occur in association with a geomagnetic disturbance by a local increase in exospheric temperature and a proportional increase in the height of the homopause. The increase in the height of the homopause is a convenient device by which to represent an effect (the inverse variation of the lighter constituents) that may actually be due more to wind-induced vertical diffusion. Superimposed on these two effects is the "equatorial wave" referred to in the introduction, in which the number densities of all constituents increase in the same proportion and that is centered on the equator. We will adopt the same representation here and model the change in the logarithm of the number density of the species i as the sum of three components:

$$\Delta_G \log n_i = \Delta_T \log n_i + \Delta_H \log n_i + \Delta_e \log n_i \qquad (1)$$

where $\Delta_T \log n_i$ is the thermal component, $\Delta_H \log n_i$ is the component due to the change in the height of the homopause and $\Delta_e \log n_i$ is the component due to the equatorial wave. The thermal component $\Delta_T \log n_i$ is to be evaluated from an atmospheric model assuming an increase in exospheric temperature $\Delta_G T_\infty$ given by

$$\Delta_G T_\infty = A\,F(\phi, \lambda) \qquad (2)$$

where A is the amplitude given by

$$A = 57.5 K_p' [1 + 0.027 \exp(0.4 K_p')] \ , \qquad (3)$$

as in the earlier model, and $F(\phi,\lambda)$ is given by

$$\begin{aligned} F(\phi, \lambda) = a_{e1} + a_{e2} \sin^n \phi + \\ \cos^2 \phi (a_{11} \sin\lambda + a_{12} \cos\lambda) + \\ \sin 2\phi (a_{21} \sin\lambda + a_{22} \cos\lambda) + \\ \sin^4 \phi \sin 2\phi (a_{31} \sin\lambda + a_{32} \cos\lambda), \end{aligned} \qquad (4)$$

where ϕ and λ are the geomagnetic latitude and local magnetic time, respectively. To take the effects of persistence into account, we assume K_p' in equation 3 to be the weighted mean of the lagged 3-hourly K_p geomagnetic index taken over the 41 values in the preceding 5-day interval as follows:

$$K_p'(t) = \frac{\sum_{t_i=t-\tau-5}^{t-\tau} K_p(t_i) e^{-c(t-t_i-\tau)}}{\sum_{t_i=t-\tau-5}^{t-\tau} e^{-c(t-t_i-\tau)}} \tag{5}$$

where t is the time in days, $c = 1.0\ d^{-1}$ and τ is the time lag given by

$$\tau = 0.05 + 0.1 \cos^2 \phi \text{ (day)} \tag{6}$$

In equation 4, the first two terms represent the mean latitudinal variation of the increase in exospheric temperature. The remaining three terms represent the variation of the temperature increase with local magnetic time (LMT) in low, middle and high latitudes, respectively. To introduce a variation in the mean shape of the latitudinal variation with the level of disturbance, we take n in equation 4 as

$$n = 5.0 - K_p'/3.0 \tag{7}$$

A preliminary determination of the remaining parameters in equation 4 was made by a least squares fit to values of the exospheric temperature increase inferred from N_2 measurements made by the ESRO4 mass spectrometer. Exospheric temperatures were obtained from N_2 densities by inverse interpolation in an atmospheric model. The temperature increase was taken to be the difference between the exospheric temperature corresponding to the observed N_2 density and that corresponding to the density computed for quiet conditions from the ESRO4 "quiet time" model of von Zahn et al (1977). The resulting coefficients are

$$\begin{aligned} a_{01} &= .1425E{+}00 & a_{02} &= .8137E{+}00 \\ a_{11} &= .1184E{+}00 & a_{12} &= -.3604E{-}01 \\ a_{21} &= -.7354E{-}01 & a_{22} &= .1038E{+}00 \\ a_{31} &= .3706E{+}00 & a_{32} &= -.1441E{+}00 \end{aligned} \tag{8}$$

The isotherms of the relative temperature increase as given by equation 4 in the case where $K_p' = 3$ ($n = 4$) are plotted over the globe in geomagnetic coordinates in figure 2. As can be seen, there is a considerable asymmetry with respect to the pole. The maximum is between 6^h and 9^h at a latitude of about 80 degrees. This probably reflects both Joule heating by the westward auroral electrojet and particle precipitation in the cusp region. The extent of the asymmetry can perhaps be better seen in figure 3, where the profiles for 6^h and 18^h LMT - near the extremes - are plotted together with the mean latitudinal profile. Of course, the difference in high latitudes as seen by an orbiting object would tend to be smoothed out over intervals on the order of a day because of the earth's rotation. This would not be the case in low latitudes, however, and it is interesting to note that, even with the poor resolution of satellite drag,

Roemer (1971) was able to detect this asymmetry in densities deduced from drag.

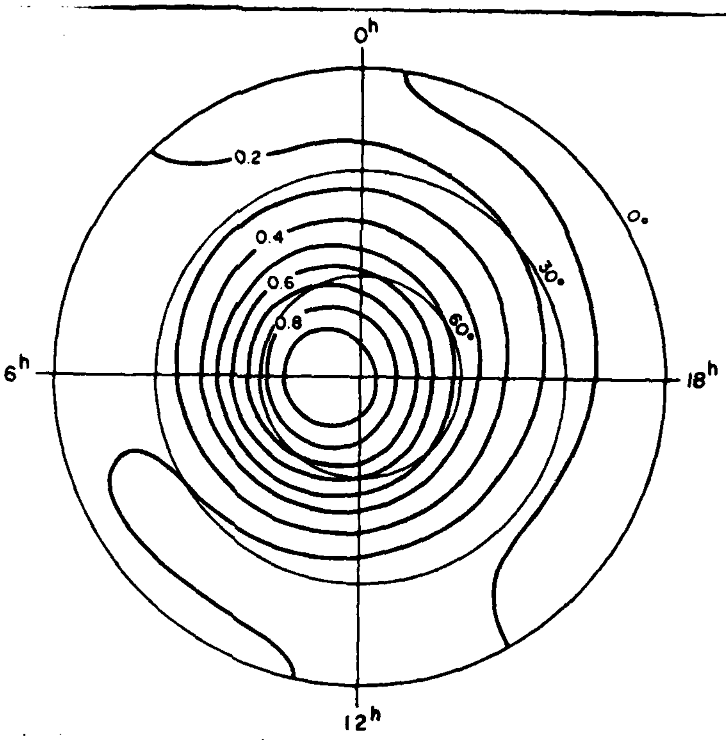

Figure 2. Global isotherms of the relative temperature increase due to geomagnetic disturbance as given by equation 4 for $K_p' = 3$. The coordinates are geomagnetic latitude and magnetic local time.

We should point out that a geomagnetic disturbance will alter the atmospheric temperature profiles, so that the procedure we have outlined of entering exospheric temperatures in a static model to determine the effects on the number densities is not strictly valid. There will be a height dependence that we have not accounted for that becomes an important consideration at lower heights. In this connection, we have developed disturbed temperature profiles that give good results in representing observed density variations at heights as low as 150 km. We have also developed expressions to represent the effects of these disturbed profiles on the number densities analytically. These expressions are rather involved, so we will not repeat them here, but they represent an integral part of the thermal component of the geomagnetic variation as we would model it.

Concerning the other two components of the geomagnetic variation, we would include them in the form given recently by Slowey (1983). Specifically, we would compute the component due to the change in the height of the homopause from

$$\Delta_H \log n_i = \alpha_i \Delta z_H, \tag{9}$$

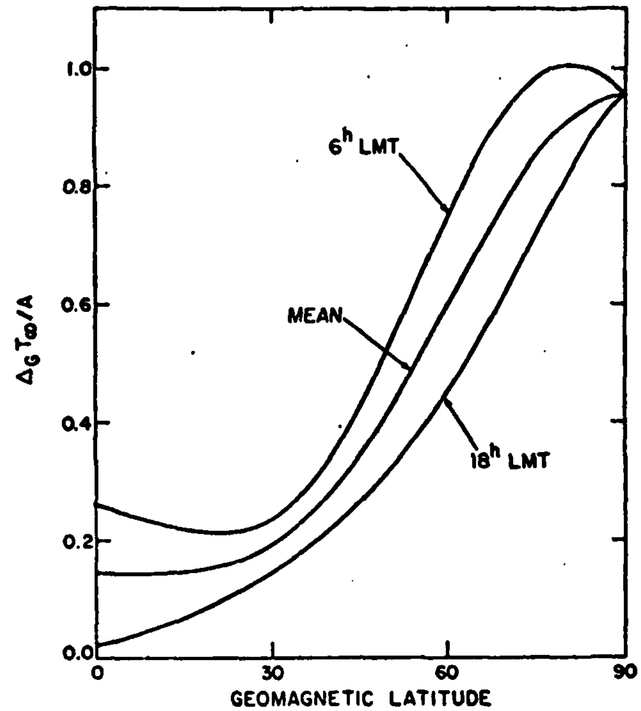

Figure 3. Latitude profiles of the relative temperature increase for $K_p' = 3$ as given by equation 4 for 6^h and 18^h LMT. The profile of the mean latitudinal variation is also shown.

where Δz_H (meters) is to be computed from

$$\Delta z_H = 22.0\, \Delta_G T_\infty \; , \tag{10}$$

where $\Delta_G T_\infty$ is given by equation 2, and the α_i's are:

$$\begin{aligned} \alpha(Ar) &= +3.07 \times 10^{-6} \quad (mks) \\ \alpha(O_2) &= +1.03 \times 10^{-6} \quad (mks) \\ \alpha(N_2) &= \;\; 0.0 \\ \alpha(O) \;\; &= -5.75 \times 10^{-6} \quad (mks) \\ \alpha(He) &= -6.30 \times 10^{-6} \quad (mks). \end{aligned} \tag{11}$$

The component due to the equatorial wave would be computed from

$$\Delta_e \log n_i = \Delta_e \log \rho = 5.2 \times 10^{-4}\, A \cos^3 \phi \tag{12}$$

where ρ is the total density and A is given by equation 3. As was mentioned in the introduction, some work remains to be done to better separate this component from the thermal component in low latitudes. Suitable data

are available from both mass spectrometer and accelerometer experiments.

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